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System reliability effects in wind turbine blades

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ABSTRACT: Laminated composite sandwich panels have a layered structure, where individual layers have randomly varying stiffness and strength properties. The presence of multiple failure modes and load redistribution following partial failures are the reason for laminated composites to exhibit system behavior from reliability point of view. The present paper discusses the specifics of system reliability behavior of laminated composite sandwich panels, and solves an example system reliability problem for a glass fiber-reinforced composite sandwich structure subjected to in-plane compression.

1 INTRODUCTION

The word “composite” originates from Latin, and literally means “made up of distinct parts”. This is indeed the most distinct feature of composite materials, which constitute of two different material phases and as a result have a number of unique properties. The combination of two material phases (fibers and matrix), arranged in multiple layers, results in a material with non-isotropic, non-homogeneous elastic strength properties, which can fail in a number of different failure modes. To the reliability engineer, the presence of distinct failure modes means that composites will exhibit system reliability behavior. This system behavior will appear on several levels, corresponding to the length scales at which the respective failure modes occur – starting from micro-scale (fibers, matrix and interface between them), through lamina (individual layers with unidirectional fibers), structural components such as laminate panels (stacks of individual laminas) and sandwich panels, and up to whole structures such as an entire wind turbine blade.

2 RELIABILITY-RELATED ASPECTS OF COMPOSITE MATERIALS

2.1 *Length scales of composites*

For the present paper the modeling domain is limited to three scale levels – individual lamina, laminated panels, and sandwich panels. Taking into account individual unidirectional lamina allows modeling the non-isotropic mechanical properties of composites, while avoiding the use of micromechanics. Including laminates and sandwich panels into the analysis allows modeling the reliability against failure of a given location within a structure – for example, a so-called “hot-spot” which is known or expected to be critically decisive for the overall safety of the structure.

2.2 *Definition of failure events*

Due to the presence of a number of layers, the failure of a laminated composite panel will often happen as a gradual event, with different layers failing in sequence. Between successive layer failures the load previously carried by the failed lamina is redistributed to the layers remaining intact. Consequently, the definition of an ultimate failure event for a composite sandwich panel can to a high extent be a matter of subjective judgement. Probably the simplest approach to defining failure is identifying the so-called "first-ply failure" event, where failure of any of the laminate components (i.e. the first failure occurring under gradually increasing load) will be considered as a total structural failure. Such an approach can however lead to very inefficient designs, because typically the first failures are associated with matrix cracking, which does not have a significant effect on the residual stiffness and strength of the structure (see Figure 1). There is also some degree of redundancy in composite structures, meaning that the structure will often be able to withstand loads higher than the load at which the first failure has occurred.

A progressive failure analysis procedure can be used to find the maximum load which the structure can withstand while maintaining static equilibrium. This is the approach which most fully describes the failure process in the panel, however it might not be very useful for design purposes, because a large amount of irreversible damage can occur at load levels below the indicated ultimate strength. Finally, the approach adopted in this paper is to use a progressive failure analysis procedure to find the load level at which the first fiber breaching occurs. The use of progressive failure analysis means that the development of matrix-related failure events will be followed until the first fiber failure occurs. Although not describing the ultimate failure, this approach might be more realistic for design purposes as the failure event is at the point when the first significant damage occurs.

2.3 *System characterization*

As discussed in the preceding paragraph, progressive failure of composite laminates is characterized by redistribution of loads following each of the successive failure events. Individual lamina will have random strength, as well as random stiffness distributions, meaning that the sequence of layer failures might be different for different realizations of the stochastic quantities. This is illustrated on Figure 1, where for two different realizations of the random lamina strength properties the sequence of failure events is different.

Loading is not uniform either – a laminate can carry loads in a number of different directions, including both forces and bending moments, meaning that there will be a varying stress field inside the laminate.

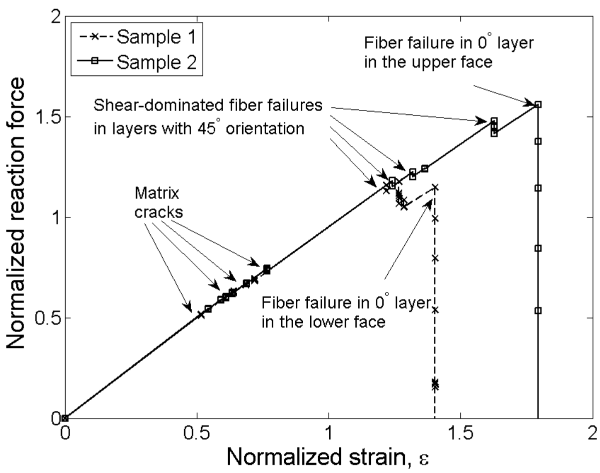

Figure 1: Path-dependent progressive failure process of a composite sandwich panel with random layer strengths

A system with the features as previously described (varying stiffness, strength, loading, and load redistribution following failures) could in principal be modeled as a parallel system, as long as the overall failure event occurred when the last system component has failed. However, according to the definitions of laminate failure given above, ultimate failure occurs when the maximum load bearing capacity of the structure has been exceeded, or significant damage has occurred. These events might happen when there are still a large number of intact layers, with the failure event triggering a cascade failure of the remaining intact layers. This shows that a composite laminate can only be characterized as a general system.

Daniels (1945) has described the properties and derived reliability bounds for a similar type of system, consisting of equally loaded wires with random strength. The behavior of composite panels bears similarities with a Daniel's system, with failure being similarly characterized as the situation when the load exceeds the remaining bearing capacity of the structure. A difference with the classical Daniel's system is the fact that the individual components in the presently discussed problem have different stiffnesses, and are possibly loaded differently.

2.4 *Solution of the system reliability problem*

While a number of approaches to solving system reliability analysis problems exist, the choice of methods capable of resolving general systems is more limited. The solution methods which the authors of this paper have reviewed can in principal be divided into four groups:

- Monte Carlo simulation methods, including crude Monte Carlo, and adaptive (search-based) importance sampling (Melchers, 1990)
- Methods involving cut-set or tie-set definitions, e.g. Sequential Compounding (Kand & Song, 2010), linear programming (Song & Der Kiureghian 2003), or direct multivariate integration of the cut set / tie set when possible
- Using order statistic, transform each of the correlated component events into independent events, and compute their joint probability distributions (Friis-Hansen 1994)
- Obtaining reliability bounds by evaluation of component failure sequences leading to a point in the safe domain, thus evaluating the probability of the safe event set (Ditlevsen & Madsen 1996)

Due to the presence of multiple layers and multiple failure modes per lamina (in the example given below there are two modes per lamina) for a typical composite panel the total number of system components becomes fairly large. However, analyzing a large system in its entirety is difficult using most of the methods listed. Given the above, three most suitable approaches to solving the present reliability problem are identified:

- Use a technique not suffering from problem dimensionality (e.g., Monte Carlo);
- Simplify the problem by identifying possible critical components and focusing the analysis on those components. Consider each of the critical components as a cut-set, i.e., its failure results in an overall system failure;
- Use FORM/SORM analysis to find a possible design point, and correct the reliability estimate for any nonlinearity in the failure surface by applying importance sampling at the design point. This analysis can serve as an indicator to the degree of system behaviour present in the structure – under milder conditions this technique should be able to determine the correct probability of failure, while if there are significant system effects present with multiple design points far from each other, the reliability estimate will not be correct.

2.4.1 *Representing laminated faces as single equivalent layers*

In sandwich panels, the thickness of the core is typically much larger than the face thickness. This means that the variation of normal stresses in the faces will be relatively small, and under certain conditions it can be disregarded, assuming that the normal stresses are constant throughout the face (see Zenkert, 1995). Under this assumption, the sandwich model can be simplified by replacing the layer-wise description of the face laminate with equivalent, homogeneous layer, thus reducing the structural system to three components – upper face, lower face, and core. If the strength distributions of faces and core are available, it is straightforward to determine the system reliability by making a three-component series system analysis.

Although very useful in deterministic stiffness and strength analysis, it is possible that the single-layer representation of the faces will result in some deviations in the reliability estimate, because not all system effects and load redistribution effects under a progressive failure process will be accounted for. Here, the extent to which a homogeneous-layer representation of the faces can be used in reliability analysis is tested by comparing a reliability model based on homogeneous faces with the reliability estimates found from a full layer-wise model.

3 EXAMPLE RELIABILITY ANALYSIS OF A COMPOSITE SANDWICH PANEL

In the following, the discussion continues with the help of an example reliability problem, where the reliability against ultimate failure of a sandwich composite panel is considered.

3.1 *Description of structure*

The structure under consideration is a simply supported, unit-width sandwich beam with faces made of glass-fiber reinforced fibers, and a balsa wood core. The two faces are identical laminates, consisting of eight layers each. Individual layers have a thickness of 0.3mm, while the core thickness is 40mm, giving a total laminate thickness of 44.8mm. The layup sequence of the faces, $\theta = [-45^\circ\ +45^\circ\ 0^\circ\ 0^\circ\ 0^\circ\ 0^\circ\ +45^\circ\ -45^\circ]$, is simple, but in principle very similar to the layup sequences typically found on wind turbine blades, where the vast majority of layers have orientation of 0 and ±45 degrees.

The sandwich beam is subject to a downward distributed load of Q_z = -7kN/m, and a compressive axial force F_x = -1400kN. This resembles a loading condition which can be typically found on the downwind surfaces of wind turbine blades.

In the typical composite structures loads are varying randomly, and are usually associated with a significant degree of uncertainty. This high uncertainty will be reflected in the reliability analysis and will make it more difficult to observe the influence of material properties. As the objectives of this study are related to material behavior, it is chosen that the load values will be deterministic, thus eliminating them as a source of uncertainty.

The presence of defects also has a significant influence to the strength of composites. However, taking defects into account needs the introduction of an additional set of theories and models, which will greatly enlarge the scope and complexity of the analysis. Therefore the materials used in the present study are considered defect-free. The influence of defects however remains an important field of study which should be addressed in future research.

3.2 *Modeling of stochastic material properties*

In order to allow for random variations in the material properties within the laminate, each layer should be represented by a separate set of stochastic variables describing the material properties. The properties of a lamina are typically characterized by 9 material constants, and for the 17-layer laminate this would mean at least 149 random variables (9 for each of the face layers, plus 5 for the core, where the transverse shear strength is the only strength property considered). Elastic properties have less variation than the strength properties, and for structures where geometric instabilities are not the dominant failure mechanism elastic properties have in general less influence on the load bearing capacity of the structure compared to the strength properties. Based on this argument, and in order to reduce the number of stochastic variables and to simplify the problem, it is decided to represent the elastic properties of materials with their mean values This results in a total of 81 stochastic variables representing the material properties.

Table 1 lists the assumed statistical distributions of the five strength parameters for composite lamina used in the present study. The properties of the face materials are determined from material test data given in the OptiDat public database (Nijssen 2006).

Table 1. Statistical distributions of strength parameters.

Parameter	Designation	Mean	Cov	Distribution
Fiber tensile strength	X_t	780MPa	0.06	Lognormal
Fiber compressive strength	X_c	528MPa	0.19	Lognormal
Matrix tensile strength	Y_t	54MPa	0.08	Lognormal
Matrix compressive strength	Y_c	165MPa	0.14	Lognormal
Lamina shear strength	S	82MPa	0.15	Lognormal
Balsa core shear strength	S_c	2.2MPa	0.1	Lognormal

The correlation structure of the material variables has to represent both the spatial variation of a given mechanical property, as well as correlation between different properties (e.g., tensile strength and shear strength). Thus the correlation coefficient between any two stochastic variables is taken as the product of two correlation coefficients,

$$\rho_{ij} = \rho_{Li,Lj} \cdot \rho_{Mi,Mj} \tag{1}$$

where

- i,j refers to the variable number
- $L(i)$, $L(j)$ are the layer numbers which variables i and j refer to
- $M(i)$,$M(j)$ are the two material properties which the variables i and j refer to, respectively.
- $\rho_{Li,Lj}$ is the correlation coefficient between the same property for different layers. It is taken as a fixed value, with $0 \le \rho_{Li,Lj} \le 1$ for $i \neq j$, and $\rho_{Li,Lj} = 1$ for $i = j$.
- $\rho_{Mi,Mj}$ is the correlation coefficient between the different material properties which variables i and j represent, regardless of layer number. The values of $\rho_{Mi,Mj}$ are taken from a study by Toft (2010), based on micromechanics laws, and are listed in Table 2.

It is considered that the core strength properties are not correlated with face properties, and that properties in different faces are not correlated either.

The value of the correlation between the strength of different layers $\rho_{Li,Lj}$ is not known with certainty, as it is in principle very difficult to determine. It is nevertheless expected that a significant degree of correlation exists, because all material layers at a certain location within the structure have been subjected to similar conditions during the casting and curing process. In order to investigate the influence of inter-layer correlations, reliability analyses are carried out with a number of different correlation levels, $\rho_{Li,Lj}$ = [0; 0.3; 0.7; 1]. Correlation level of $\rho_{Li,Lj}$ = 1 will mean that all layers in a single face will have the same strength properties.

Table 2. Correlation coefficients between material strength variables.

	Xt	Xc	Yt	Yc	S
Xt	1	0.8	0	0.2	0.2
Xc	0.8	1	0	0.2	0.2
Yt	0	0	1	0.8	0.8
Yc	0.2	0.2	0.8	1	0.8
S	0.2	0.2	0.8	0.8	1

3.3 *Evaluation of ultimate capacity of the sandwich model*

The stress distribution within the panel is calculated using the assumption that the core is loaded primarily in shear, with negligible normal stresses, while the faces carry the normal stresses with negligible transverse shear loading (see Zenkert, 1995). The layer-wise stress distribution is calculated using Classical Lamination Theory, a method described in Jones, 1998. In order to determine the failure load, a step-by-step analysis is performed, where at each step the layer which will fail under the smallest load is identified. The mechanical properties of the failing layer are downgraded, the structure is updated, and a new analysis step is performed on the remaining layers. The procedure is interrupted when a fiber-mode failure is observed, which will typically happen after a number of matrix-mode failures have already occurred, which is also visible on Figure 1.

The load at which a lamina fails is identified using the Hashin composite failure criterion (Hashin, 1980). This failure criterion assumes that a lamina can fail in two distinct modes: fiber failure or shear-dominated matrix failure. Both matrix and fiber failures can be tensile or compressive, depending on the stresses acting on the lamina.

3.4 *System reliability*

The reliability of the structure described above is estimated using the three different approaches suggested in section 2.4, as well as using a model where laminate faces are represented as single equivalent layers. A comparison of the performance of these four approaches is given in the following.

3.4.1 *Crude Monte Carlo*

Given that enough failure events are observed, crude Monte Carlo (MC) simulations are probably the most robust method for determining reliability, and are therefore used as a reference value here. All simulations used in the present study are run until at least 400 failure events have been observed, which according to the formula by Shooman (1968) corresponds to a 95% confidence that the error in the reliability estimate is less than 10%.

The results from the Monte Carlo simulations have identified that the layers in the face laminate oriented at 0 degrees are the most critical for the integrity of the structure (in most of the samples, indicating failure, the structure loses static equilibrium and collapses in a cascade of failures, following failure of one of the aforementioned 0-degree layers). In an attempt to simplify the problem and make use of more efficient reliability methods, this observation can be used as means to restrict the system analysis to the most critical parts of the structure.

The effects of correlation between properties of different lamina are also clearly visible from the MC simulations. As Figures 2.a) and 2.b) illustrate, in the case of uncorrelated material strengths in different lamina, the ultimate failure event is located at various layers, mostly the four layers with 0-degree orientation of the upper face. In the case of fully correlated layer strengths within the face laminates, almost all failure events are concentrated at a single layer, which is the highest-loaded layer with 0° fiber angle. Such a behavior is expected, as when all the lamina in a given laminate have the same properties, the one failing first will simply be the one subject to the highest stress.

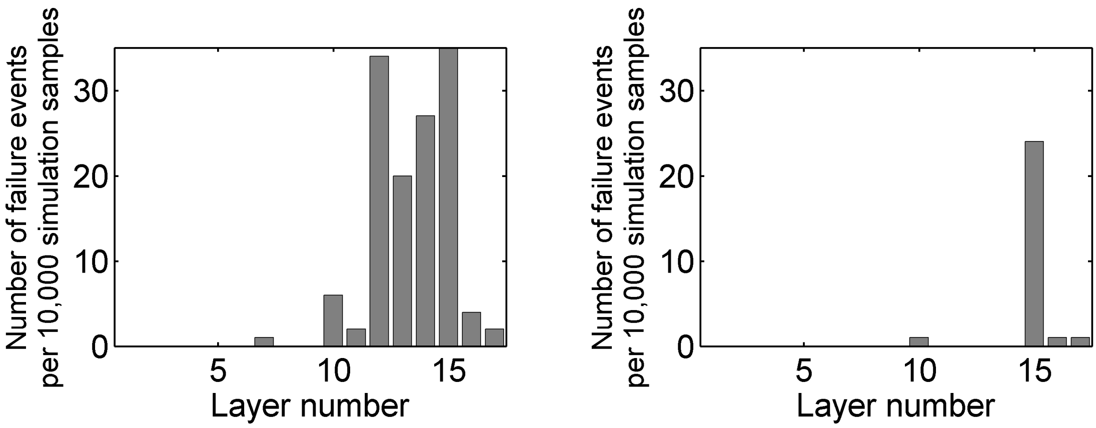

Figure 2: Location of layers where first fiber fracture is observed during a Monte Carlo simulation
a) No correlation between lamina properties b) Full correlation between lamina properties

Results from Monte Carlo simulations, along with results from other used methods, are shown on Figure 3.

3.4.2 *Series system of critical components*

The results from the Monte Carlo simulations showed that some of the layers (the ones with 0-degree orientation) are the most critical to the integrity of the structure. If it is assumed that failure of any of these layers will lead to the ultimate collapse of the panel, each of the layers can be considered as a cut-set consisting of a single component. The reliability of each of these sets is equal to the component reliability, which, using single-component FORM analysis, is found to be $\beta_{component}$ = [2.586, 2.574, 2.562, 2.550] for the four 0-degree layers loaded in compression. System failure probabilities can be then estimated by $P_{f,cut\text{-}set} = 1 - \Phi_N(\beta_{component}, R_{component})$, where $\Phi_N()$ denotes the N-dimensional multivariate normal distribution, and N is the number of components under consideration.

3.4.3 *Equivalent layer model*

The stochastic distributions of the equivalent strengths of the laminate faces used in the present problem are determined using simulation. For small failure probabilities, the tail of the strength distributions will have the greatest importance, and in order to ensure a good estimate some tail approximation technique has to be employed, as for example the ACER method by Naess (2009). For the present problem the probabilities of failure are relatively large, and a simple fit of a lognormal distribution to the data set from the MC simulation results gives excellent results too. The total probability of failure is then calculated by assuming a series system of three components (lower face, core, and upper face).

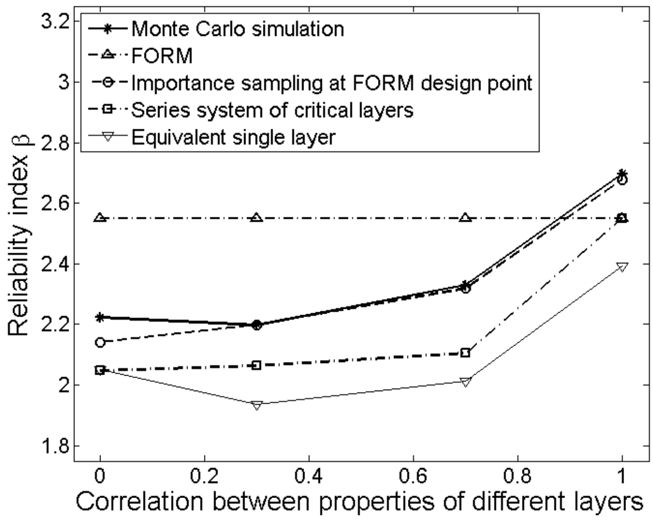

Figure 3: Results from system reliability analysis

3.4.4 *Comparison of results*

System reliability estimates obtained by all the methods discussed above are shown on Figure 3. The presence of system behavior is evident when looking at the performance of FORM method, which fails to predict the correct reliability index, and converges to the same design point, regardless of the degree of correlation between layers. This design point corresponds to failure of the 0-degree layer which is subjected to highest load (layer number 15, counting from the laminate bottom surface). However, due to the randomness in material properties, failure modes corresponding to layers with lower stress are also present.

Importance sampling runs, centered at the design point obtained from FORM, converge to the correct probability of failure in most of the cases considered; however the convergence is very slow, because the sampling center points correspond to a single failure mode. Other failure modes occur relatively rarely, because their probability densities are far apart from the sampling center point. As a result, the importance sampling procedure described above has efficiency similar to that of a crude MC simulation, because the importance sampling density maximizes the chances of occurrence of just one of the several failure modes present.

The two simplified approaches for solving the system problem (using a smaller part of the system, or representing the faces as homogeneous) both capture the main trends in the system behavior, however the reliability estimates are conservative, sometimes with significant difference from the reference MC simulation results. These differences are explained by the facts that with such simplified representations the redistribution of stresses between the two sandwich faces following matrix-mode failures cannot be captured. The accuracy of the homogeneous layer representation is further limited by the underlying assumption that the stresses are constant throughout the laminate face.

4 DISCUSSION AND CONCLUSIONS

The problem of estimating the reliability against ultimate failure of composite sandwich panels has been discussed. Based on the properties of composite panels, including random strength and stiffness of layers, load redistribution under successive failures, and ultimate failure load dependent on the sequence of prior failures, it is suggested that the composite structure is best represented by a general reliability system.

Reliability of the general system has been calculated using the Monte Carlo approach. It is noted that the 0-degree layers (where fibers are oriented along the load direction) are critical for the integrity of the structure, and failure of these layers often leads to overall system failure. Based on such observations, it is possible to implement reliability methods more efficient than crude simulation, by considering only the parts of the system corresponding to the most critical layers identified. In this way a crude approximate estimate of the system reliability can be obtained, with some inaccuracy caused by the lack of account for the load redistributions following failure events.

Another way for simplifying a composite sandwich model is the commonly used approach of representing the laminated faces as equivalent homogeneous layer. Using this approach allows to capture some of the characteristics of the reliability problem, however it does not account for load redistributions following partial layer failures, and it does not account for the (small) variation of stresses throughout the face thickness. As a result, representing the laminated faces as equivalent homogeneous layers results in a reliability estimate differing from the reference Monte Carlo calculation. Although being relatively inaccurate, the single homogeneous layer calculation yields an approximate, conservative estimation of the system reliability, and can be useful in some reliability calculations where model complexity will not allow the use of full layerwise representation of the sandwich faces.

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